PAPER NUMBER 59-LUB-11

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Effect of Hardness, Surface Finish and Grain Size on Rolling Contact Fatigue Life of M50 Bearing Steel

R. A. BAUGHMAN

Manager, Materials Application
Unit, General Electric Company,
Flight Propulsion Laboratory Department,
Cincinnati, Ohio.

The effect of hardness, surface finish and grain size upon the compressive rolling contact fatigue strength of M-50 bearing steel has been studied. Considerable testing on the RC Rig and statistical treatment methods have been included. A mathematical expression relating these variables to life expectancy is presented and the optimization of these variables is discussed. It is shown that bearing fatigue of M50 increases by increasing hardness, decreasing surface, and increasing grain size. The optimum life identified occurs at Rc 64 hardness, 1.5 RMS surface finish, and a grain size of ASTM 2.

E AMERICAN SOCIETY OF MECHANICAL ENGINEERS
29 West 39th Street, New York 18, N. Y.

Contributed by the Lubrication Division of The American Society of Mechanical Engineers for presentation at the ASME-ASLE Lubrication Conference, New York, N. Y., October 20-22, 1959. Manuscript received at ASME Headquarters, July 10, 1959.

Written discussion on this paper will be accepted up to November 20, 1959.
Copies will be available until August 1, 1960.

Effect of Hardness, Surface Finish and Grain Size on Rolling Contact Fatigue Life of M50 Bearing Steel

R. A. BAUGHMAN

Specifications set for antifriction bearing procurement, including hardness, grain size and surface finish are based primarily on results obtained through experience on full-scale bearing tests. This technique is satisfactory and has resulted in excellent progress in bearing development. It is, however, fallacious to assume that bearing tests are the ideal manner to study isolated variables because of the numerous other variables which are part of the manufacturing cycle and which may affect life. The difficulty of isolating one particular variable for the purpose of evaluation by bearing tests is overwhelming. The development of the RC Rig[1] has made possible the isolation and study of one variable at a time.

In order to determine the significance of these variables as related to bearing life for design and manufacturing purposes, the primary and secondary effects of these variables upon fatigue life must be separated and analyzed. This is necessary in order to establish optimum conditions for these variables. Stress level is another variable included to introduce some flexibility to the applicability of the results.

In order to separate the effects of the variables upon fatigue life, a statistical approach is used. A complete description of the statistical techniques employed in designing this statistical experiment and in analyzing the statistical results is beyond the scope of this paper. It is sufficient to note, however, that the several variables affecting life are separated by various regression methods and by advanced methods of order statistics.

The material used for this investigation was a Vanadium Alloy's air-melted heat of M-50, Heat No. 52006. A series of heat-treat studies was conducted to obtain the desired range of hardness and grain size. Austenitizing was accomplished at 2200 F with time increasing for increased grain size. Double-tempering treatments were always used with temperature increased to decrease hardness. Hardness was checked by macro and micro hardness tests, grain size by metallographic examinations. To obtain the surface-finish range desired, different grades of grinding wheels were used on the centerless grinder.[2] Metallographic polishing techniques were imployed on extremely fine surface finish levels (1.5 RMS). Surface finish was checked via standard profilometer instruments.

[1] R. A. Baughman, "Experimental Laboratory Studies of Bearing Fatigue," ASME Technical Digest, December 1958, Paper No. 58-A-235.

[2] The RC Rig utilizes cylindrical specimens 3 in. long and 3/8 in. diam.

TABLE 1 EXPERIMENTAL TEST RESULTS

Hardness (Rc)	Grain Size (ASTM)	Surface Finish (r.m.s.)	Maximum Hertz Stress (10^{-3} psi)	Cycles to Failure x 10^6 #1	#2	#3	#4
64	7	9.35	700	1.121	3.190	5.620	10.429
62 1/4	10.4	3.75	665	1.159	3.409	7.239	12.56
62 1/4	3.4	3.75	665	6.248	12.288	19.04	22.69
62 1/4	10.4	14.75	665	1.001	2.968	6.771	13.144
62 1/4	3.4	14.75	665	2.446	3.469	4.69	11.723
62 1/4	10.4	3.75	732	.991	1.43	3.26	4.95
62 1/4	3.4	3.75	732	3.487	4.199	6.109	10.076
62 1/4	10.4	14.75	732	.961	3.165	7.019	11.24
62 1/4	3.4	14.75	732	.926	2.46	5.82	8.11
58	12	9.75	700	1.011	3.240	4.690	5.875
58	2	9.75	700	.989	2.004	3.960	6.105
58	7	9.75	700	1.74	2.87	4.89	10.29
58	7	1.5	700	1.902	3.284	4.229	5.149
58	7	17	700	2.436	5.356	6.195	7.520
58	7	9.75	645	2.166	3.607	5.07	8.060
58	7	9.75	745	.897	1.001	1.740	2.69
54	10.4	3.75	665	.656	1.102	2.69	2.79
54	3.4	3.75	665	.697	1.11	1.94	2.69
54	10.4	14.75	665	.487	.697	1.80	2.03
54	3.4	14.75	665	.412	1.012	1.724	2.181
54	10.4	3.75	732	.248	.629	1.209	2.667
54	3.4	3.75	732	.379	.862	1.169	1.665
54	10.4	14.75	732	.246	.296	.315	.712
54	3.4	14.75	732	.361	.605	.744	1.435
52	7	9.75	645	.471	.329	.487	1.002

TABLE 2 TABULATION OF B_{10} AND B_{50} AND THE WIEBULL SLOPE OF RC RIG FATIGUE RESULTS ON M50 AT VARIOUS GRAIN SIZES, HARDNESSES, AND SURFACE FINISHES

Hardness	Grain Size	Surface Finish	Stress(1)	B_{10} Life	B_{50} Life	Wiebull Slope
64	7.0	9.35	700	.7	4.3	1.11
62¼	10.4	3.75	665	.64	3.9	1.12
62¼	3.4	3.75	665	4.8	10.3	2.00
62¼	10.4	14.75	665	.5	4.4	0.91
62¼	3.4	14.75	665	1.4	5.2	1.55
62¼	10.4	3.75	732	.56	2.3	1.50
62¼	3.4	3.75	732	2.1	6.1	2.10
62¼	10.4	14.75	732	.56	4.4	0.97
62¼	3.4	14.75	732	.52	3.3	1.09
58	12.0	9.75	700	.78	3.3	1.35
58	2.0	9.75	700	.60	2.9	1.30
58	7.0	9.75	700	1.0	4.3	1.34
58	7.0	1.5	700	1.6	3.7	2.30
58	7.0	17.0	700	2.1	5.2	2.19
58	7.0	9.75	645	1.5	4.4	1.79
58	7.0	9.75	745	.55	1.5	2.21
54	10.4	3.75	665	.50	1.7	1.71
54	3.4	3.75	665	.47	1.6	1.73
54	10.4	14.75	665	.32	1.30	1.79
54	3.4	14.75	665	.35	1.35	1.50
54	10.4	3.75	732	.14	1.00	1.05
54	3.4	3.75	732	.25	.94	1.53
54	10.4	14.75	732	.16	.38	2.07
54	3.4	14.75	732	.25	.74	1.85
52	7.0	9.75	645	.17	.48	1.87

(1) Max. Hertz stress (10^{-3} psi).

TABLE 3 TABULATED TEST RESULTS OF B_{10} LIFE IN DESCENDING ORDER

No.	Hardness (Rc)	Grain Size (ASTM)	Surface Finish (r.m.s.)	Maximum Hertz Stress(10^{-3}Psi)*	B_{10} Life** (Cycles)
1	62 1/4	3.4	3.75	700	3.4×10^6
2	58	7	17	700	2.1×10^6
3	58	7	1.50	700	1.6×10^6
4	58	7	9.75	700	1.0×10^6
5	62 1/4	3.4	14.75	700	$.95 \times 10^6$
6	58	12	9.75	700	$.78 \times 10^6$
7	64	7	9.75	700	$.70 \times 10^6$
8	62 1/4	10.4	3.75	700	$.60 \times 10^6$
9	58	2	9.75	700	$.60 \times 10^6$
10	62 1/4	10.4	14.75	700	$.53 \times 10^6$
11	54	3.4	3.75	700	$.33 \times 10^6$
12	54	10.75	3.75	700	$.31 \times 10^6$
13	54	3.4	14.75	700	$.28 \times 10^6$
14	54	10.4	14.75	700	$.25 \times 10^6$
15	52	7	9.75	700	$.17 \times 10^6$

* All data reduced to 700,000 psi from test data.

** Test speed = 30,000 cycles/minute.

To eliminate the effect of dissimilar variables in the RC Rig rollers, the rollers were mated identically with each set of test bars. That is, at any given condition of the test bars, the rollers had identical grain size, hardness, and surface finish.

Mil-L-7808 lubricant at 20 drops per min (equivalent to flooding) was used throughout the test program. All tests were run at room temperature.

EXPERIMENTAL TEST RESULTS

The results of experimental fatigue tests are given in Table 1. Four tests were conducted at each combination of grain size, hardness, surface finish, and stress level. As expected, great variations in fatigue life were exhibited in spite of the fact that four repetitive tests were run under identical conditions. This variation in life (scatter) is due to the property that any finite collection of test results for a fixed set of conditions belongs to some definite population, defined by the manner in which the fatigue lives of the individual members are distributed within the population. An estimate of this population is obtained by constructing a graphical picture of the data commonly plotted in Weibull[3] form is a plot of the per cent of tests failed as the ordinate versus the cycle to failures as the abscissa. This distribution is linear when plotted on Weibull distribution paper. Values obtained from such plots are given in Table 2.

TABLE 4 TABULATED TEST RESULTS OF B_{50} LIFE IN DESCENDING ORDER

No.	Hardness (Rc)	Grain Size (ASTM)	Surface Finish (r.m.s.)	Maximum Hertz Stress(10^{-3}Psi)*	B_{50} Life** (Cycles)
1	62 1/4	3.4	3.75	700	10×10^6
2	58	7	17	700	5.1×10^6
3	62 1/4	10.4	14.75	700	4.8×10^6
4	62 1/4	10.4	3.75	700	4.1×10^6
5	62 1/4	3.4	14.75	700	4.3×10^6
6	64	7	9.75	700	4.3×10^6
7	58	7	1.5	700	3.6×10^6
8	58	12	9.75	700	3.3×10^6
9	58	2	9.75	700	2.8×10^6
10	58	7	9.75	700	2.8×10^6
11	54	3.4	3.75	700	1.2×10^6
12	54	10.4	3.75	700	1.3×10^6
13	54	3.4	14.75	700	1.0×10^6
14	54	10.4	14.75	700	$.80 \times 10^6$
15	52	7	9.75	700	$.48 \times 10^6$

* All data reduced to 700,000 psi from test data.

** Test speed = 30,000 cycles/minute.

The use of only four tests for each condition of grain size, hardness, and surface finish is admittedly a bare minimum. Its justification is based upon reproducibility studies, previously published[1] of the RC Rig method for rolling contact testing. The simplicity of the testing method tends to reduce the scatter and therefore the number of tests necessary to establish the position and slope of the Weibull graph. It has been ob-

[3] Weibull, "A Statistical Distribution Function of Wide Applicability," Journal of Applied Mechanics, September, 1951.

TABLE 5 EXPERIMENT TO DETERMINE THE EFFECT OF HARDNESS, GRAIN SIZE, SURFACE FINISH AND STRESS ON LIFE OF BEARING MATERIALS

Summary of Results

Variables Z_1 = Hardness, Rc; Z_2 = Grain Size, ASTM; Z_3 = Surface Finish, RMS; Z_4 = Stress PSI, Max. Hertz x 10^3

Coefficients of the General Equation $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{44} X_4^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{34} X_3 X_4$

Based Upon	Y_1 Arithmetic Mean	Y_2 Mean Log of Values	Y_3 M = Shape Parameter For Weibull Distribution	Y_4 Θ = Scale Parameter For Weibull Distribution	Y_5 10% Life Based on Order Statistics	Z_3 M = Shape Parameter Eliminating Z_3, Z_4
β_0	3786878.8	15.083532	2.3294455	4269427.7	1185578.4	2.6568947
β_1	2212030.3	.72147809	- .13181985	2457279.9	559151.9	- .13273504
β_2	- 468309.3	- .10982447	- .14732217	- 562745.0	- 331716.4	- .14914162
β_3	- 361559.3	- .098833920	- .076719218	- 426937.9	- 245798.9	
β_4	- 1062018.1	- .27899127	- .017606245	- 1189920.1	- 372022.7	
β_{11}	- 329260.1	- .38992290	- .35422400	- 394921.2	- 358933.4	- .34247003
β_{22}	- 18010.3	- .047403734	- .25056545	- 19012.3	- 124135.0	- .25952200
β_{33}	371253.5	.092815924	.35110697	399306.2	3[illegible]1980.6	
β_{44}	- 10873.9	- .12882581	- .027657244	- 6529.1	027343.0	
β_{12}	- 538209.0	- .065515940	- .068761037	- 639619.0	- 366082.2	- .069088010
β_{13}	- 343922.9	.029184701	- .15323202	- 411832.6	- 307471.2	
β_{14}	- 504700.5	.032902285	.060736312	- 556773.7	- 173566.7	
β_{23}	671914.7	.072646280	.14490886	750158.4	332411.8	
β_{24}	335794.6	- .0090334937	.013692799	398184.3	211783.7	
β_{34}	576704.3	.038707809	.035174848	642937.9	216832.5	
Identification of Variables						
X_1	$\frac{\text{Hardness} - 58.08000}{3.711307}$	Same	Same	Same	Same	Same
X_2	$\frac{\text{Grain Size} - 6.936000}{3.137245}$	Same	Same	Same	Same	Same
X_3	$\frac{\text{Surface Finish} - 9.390000}{4.920915}$	Same	Same	Same	Same	Same
X_4	$\frac{\text{Stress} - 696.440000}{32.093770}$	Same	Same	Same	Same	Same
Analysis of Variance						
MS Due to Regression	1353382928. x 10^4	1.21756429	.45666929	17.00584642. x 10^4	2025601928. x 10^3	.68829200
MS Error	388869400. x 10^4	.13582000	.19581600	491042500. x 10^4	909144500. x 10^3	.25842474
F Ratio	3.4803	8.9645	2.3321	3.4632	2.2280	2.6634
Significance Level	5%	1%	10[illegible]	5%	Almost 10%	10%

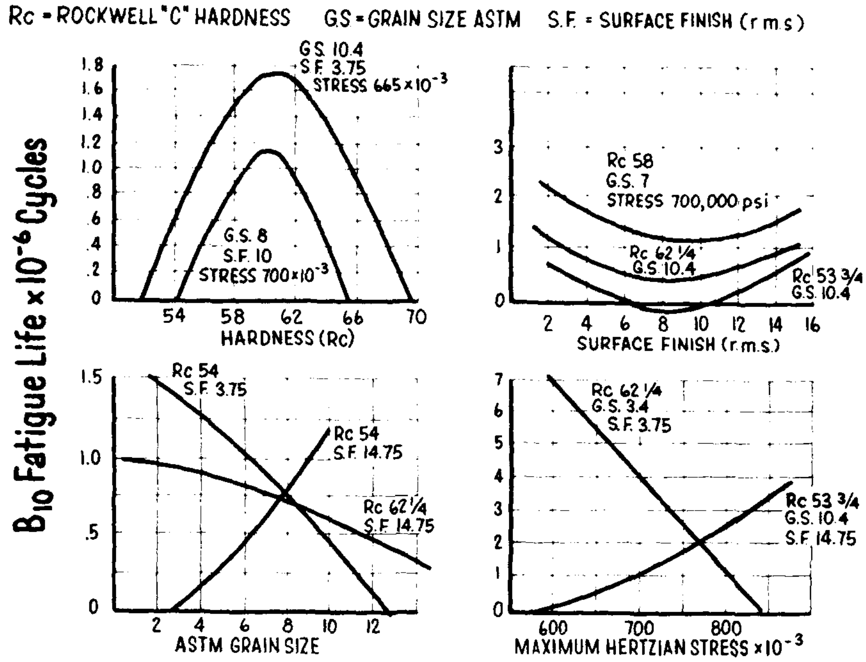


Fig. 1 Graphical representation of B_{10} fatigue life equation

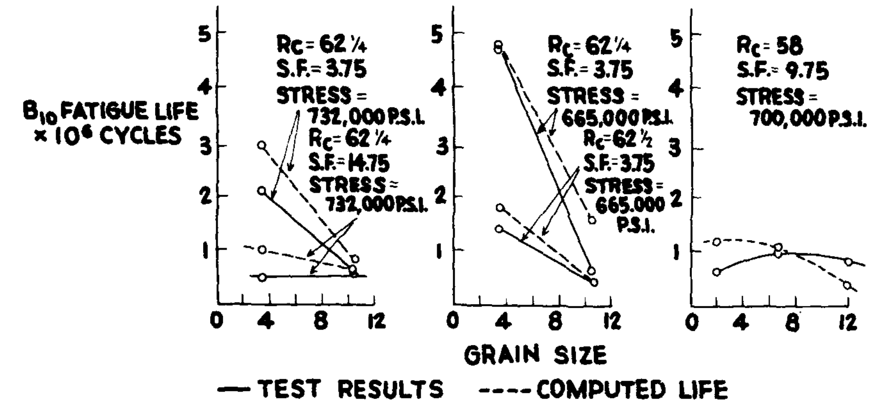


Fig. 2 Comparison of computed and experimentally obtained B_{10} fatigue life versus grain size

served that slope and position of the values studied move only slightly when based on more than four test points.

In order to compare the test results on an equal basis, these results are evaluated and compared at the same stress level. This was accomplished by interpolation of B_{10} and B_{50} lives of the repetitive tests between stress levels, assuming a linear variation between stresses. The lives at 700,000 psi are tabulated in Table 3 according to decreasing B_{10} life, and Table 4 according to decreasing B_{50} life. These results indicate that B_{50} life is predominantly dependent upon hardness while B_{10} life is dependent upon the interaction of hardness, grain size and surface finish.

GENERAL FATIGUE LIFE EQUATION

The general equation relating hardness, surface finish, and grain size to fatigue life as obtained from a statistical analysis of the test data is of the following form:

$$Y = \beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4\ldots+\beta_{11}X_1{}^2+\beta_{22}X_2{}^2+\beta_{33}X_3{}^3$$
$$+\beta_{44}X_4{}^2+\beta_{12}X_1X_2\ldots+\beta_{13}X_3+\beta_{14}X_1X_4+\beta_{23}X_2X_3$$
$$+\beta_{24}X_4\ldots+\beta_{34}X_3X_4$$

where

Y = same measure of fatigue life
X_1 = a function of hardness
X_2 = a function of grain size

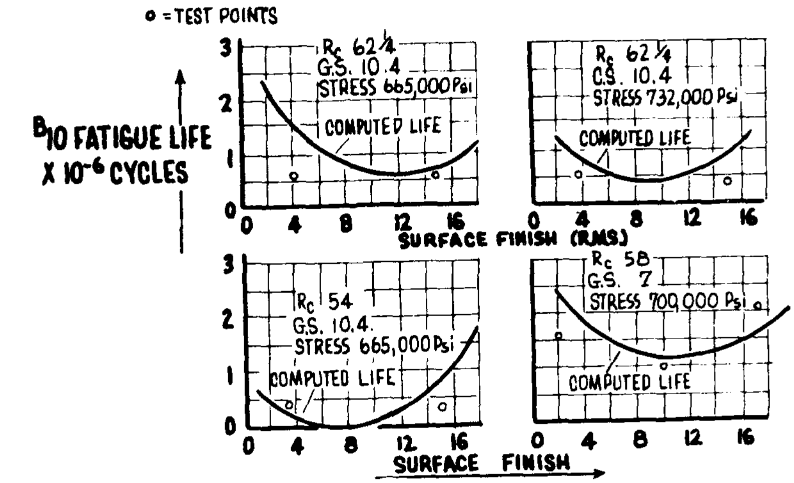


Fig. 3 Comparison of computed and experimentally obtained B_{10} fatigue life versus surface finish

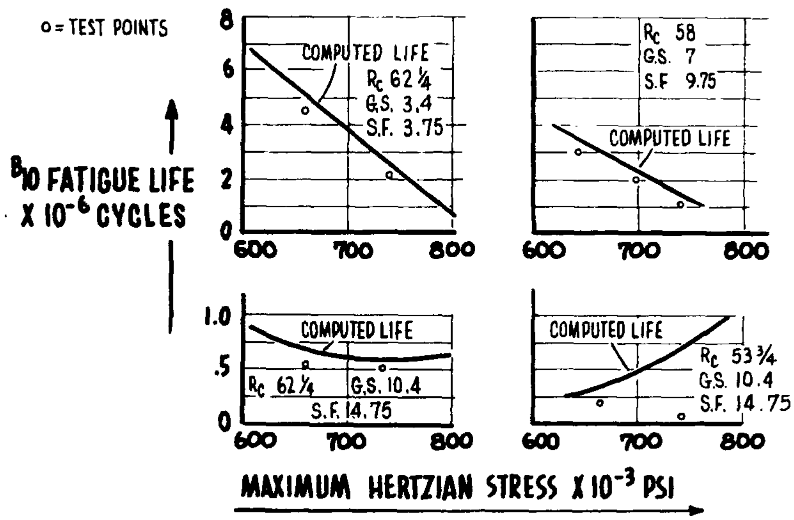


Fig. 4 Comparison of computed and experimentally obtained B_{10} fatigue life versus maximum Hertzian stress

X_3 = a function of surface finish

X_4 = a function of maximum Hertzian stress

β = general coefficient to be determined by statistical methods applied to test data

As can be seen from this equation, both the independent and the interaction effects of hardness, grain size and surface finish are considered. This equation also includes the maximum Hertz stress as a variable.

RESULTS OF STATISTICAL ANALYSIS (B_{10} LIFE EQUATION)

The results of the statistical approach are tabulated in Table 5. As can be seen from the table, the various coefficients of the general life equation are evaluated for different measures of fatigue life. One commonly used measure is the B_{10} fatigue life. The B_{10} life of a collection of tests is the life up to which 10 per cent of tests in a population will have failed. This life is of primary interest in that we are generally more interested in being able to predict the occurrence of early failures rather than the magnitude of the mean life. While it is not possible to predict the B_{10} life from a given number of failures with the same degree of confidence as that obtained for the mean life, the statistical results of this analysis are at a significant level of almost 10 per cent.

Representative graphical presentations of the

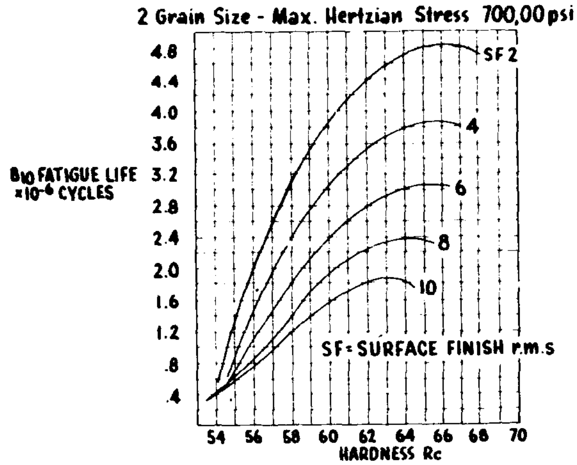


Fig. 5 B_{10} fatigue life versus hardness

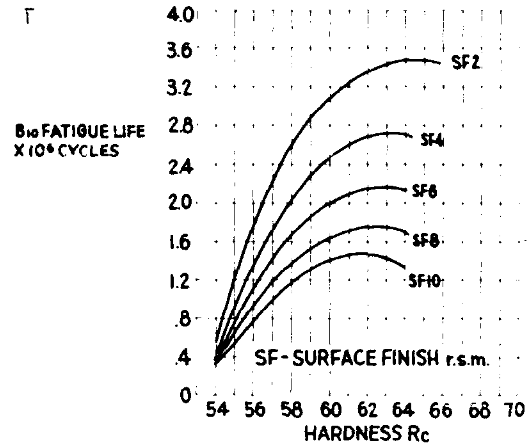


Fig. 7 B_{10} fatigue life versus hardness - grain size-6 - maximum Hertzian stress 700, 000 psi

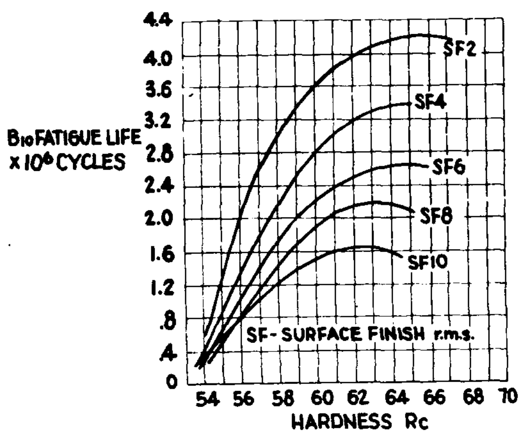


Fig. 6 B_{10} fatigue life versus hardness-grain size-4 - maximum Hertzian stress 700, 000 psi

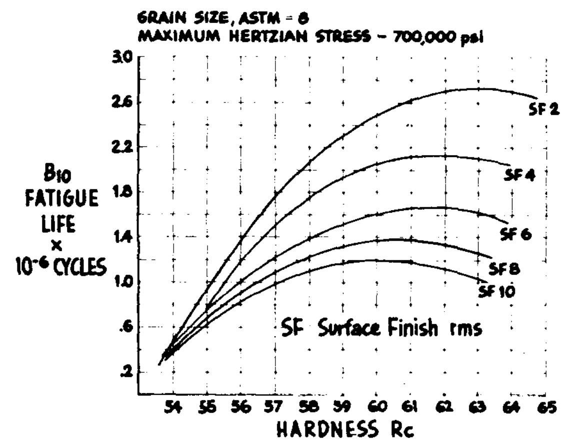


Fig. 8 B_{10} fatigue life versus hardness

results of the B_{10} life equation are shown in Fig.1.

DISCUSSION OF RESULTS PREDICTED BY THE B_{10} LIFE EQUATION

The effects of hardness, stress, surface finish, and grain size upon the B_{10} fatique life of M-50 are expressed by the B_{10} life equation are shown in Fig.1. As can be seen from the curve, this mathematical expression predicts lives which are negative for various combinations of the test variables. This equation also predicts an increase in life as the stress level increases for other combinations of these variables. These peculiar results may be attributed to the fact that the initial general equation is of a quadratic form for each variable. In effect, this assumes that each variable produces a life which passes through either a minimum or a maximum as the variable is monitorically increased.

Graphical comparisons of the test results and the results obtained from the empirical B_{10} fatigue life equation are made in Figs.2, 3, and 4.

Fig.2 shows that a close correlation exists between the mathematically predicted effects of grain size upon the B_{10} life and the effects of grain size obtained experimentally.

The effect of surface finish upon life, however, is not clearly defined. Although Fig.3 shows a good correlation between the mathematically predicted and experimentally obtained lives, only Fig.3(d) substantiates the result that a minimum life occurs at a surface finish of about 10 rms. It is felt that these predicted minimum lives are greatly influenced by a set of high lives obtained at a surface finish of 17 rms (see Table 3). Since only one set of test data is obtained at this rela-

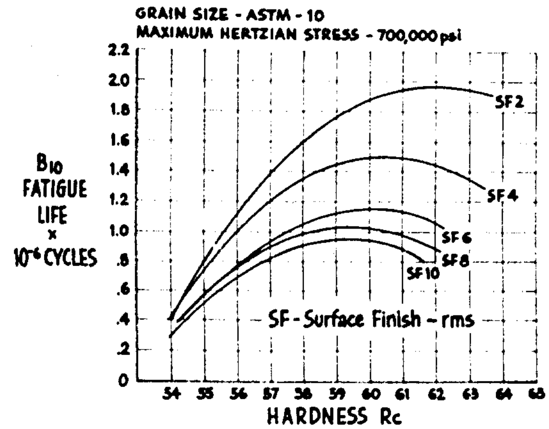


Fig. 9 B_{10} fatigue life versus hardness

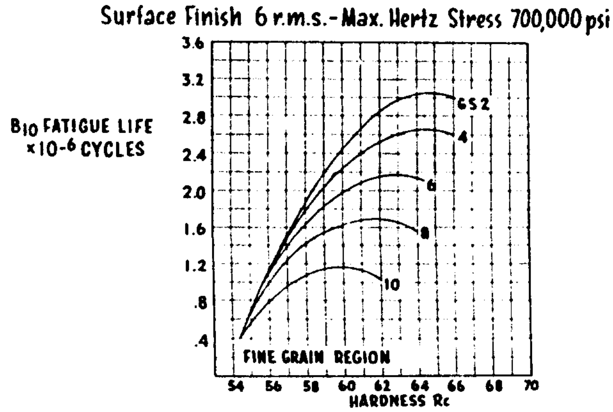
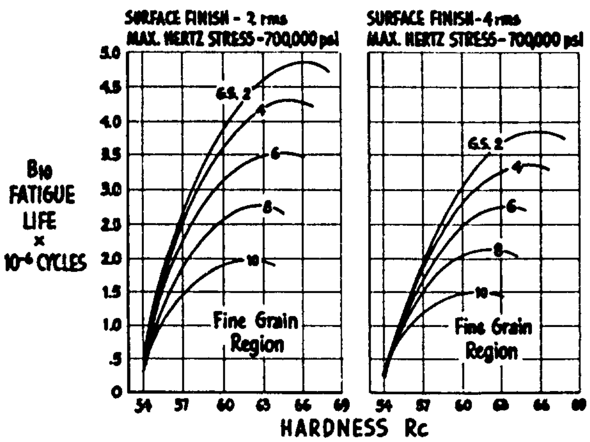


Fig. 12 B_{10} fatigue life versus hardness



Figs. 10 and 11 B_{10} life versus hardness

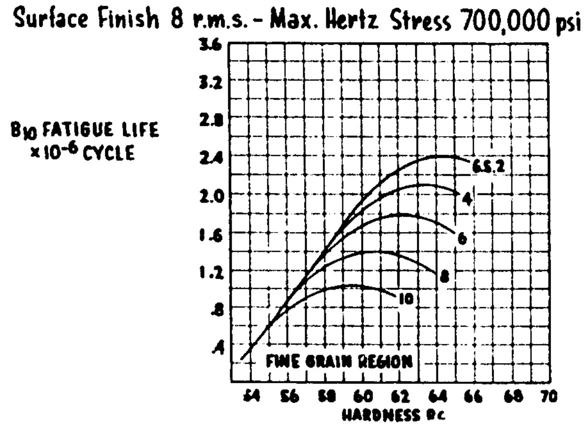


Fig. 13 B_{10} fatigue life versus hardness

TABLE 6 CONVERSION TABLE

Rc	X_1	G.S.	X_2	S.F.	X_3	Stress x 10^{-3}	X_4
50	-2.177130	1	-1.892105	1	-1.704967	600	-3.00494
51	-1.907683	2	-1.573354	2	-1.501753	610	-2.69335
52	-1.63823	3	-1.25460	3	-1.298538	620	-2.38177
53	-1.368789	4	- .935852	4	-1.095324	630	-2.070183
54	-1.09934	5	- .617101	5	- .892110	640	-1.75859
55	- .82989	6	- .298350	6	- .688896	650	-1.447009
56	- .560449	7	- .020400	7	- .485682	660	-1.13542
57	- .2910025	8	.339151	8	- .282467	670	- .82383
58	- .0215574	9	- .657902	9	- .079253	680	- .512248
59	.247891	10	.97665	10	.1239606	690	- .2006619
60	.517337	11	1.29540	11	.327174	700	.110924
61	.78678	12	1.61414	12	.530381	710	.422511
62	1.05623	13	1.9329	13	.73360	720	.734098
63	1.32567	14	2.2516	14	.93681	730	1.045685
64	1.59512	15	2.57040	15	1.14003	740	1.357275
65	1.86457	16	2.88915	16	1.34324	750	1.6688
66	2.13401	17	3.20791	17	1.54640	760	2.036531
67	2.40346	18	3.526610	18	1.74967	770	2.29203
68	2.672912	19	3.84512	19	1.95288	780	2.60362
69	2.94235	20	4.164163	20	2.156102	790	2.91520
70	3.211805	21	4.482914			800	3.2267
71	3.481252	22	4.80166				
72	3.75069	23	5.120416				
73	4.020146	24	5.439167				
74	4.28959	25	5.757918				
75	4.55903						
76	4.82848						
78	5.097933						
79	5.63682						
80	6.9062738						

tively coarse surface finish, any conclusions based predominantly upon this data must be questioned.

From Fig.4, we find that the equation relating stress to life is not valid for certain combinations of grain size, hardness, and surface finish. In view of these shortcomings, the discussion of the results must be restricted within certain limiting values of each variable.

This discussion of results which follow are valid for hardnesses greater than 54 RC, grain size larger than ASTM 10, and surface finishes better than 10 rms. In order to simplify the B_{10} equation, the stress variable is eliminated by evaluating all lives at a modified Hertz stress of approximately 700,000 psi. The resulting equation is called the "Modified B10 Fatigue Life" equation since it eliminates all of the stress dependent terms.

THE "MODIFIED B_{10} FATIGUE LIFE" EQUATION

In order to obtain our modified equation, the general life equation is rewritten as follows:

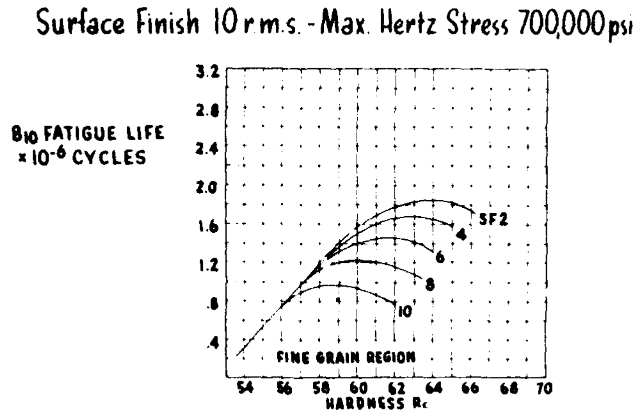


Fig. 14 B_{10} fatigue life versus hardness

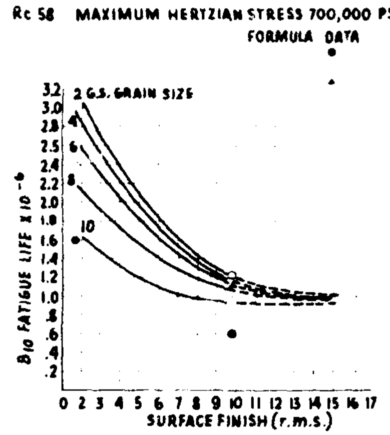


Fig. 16 B_{10} fatigue life versus surface finish

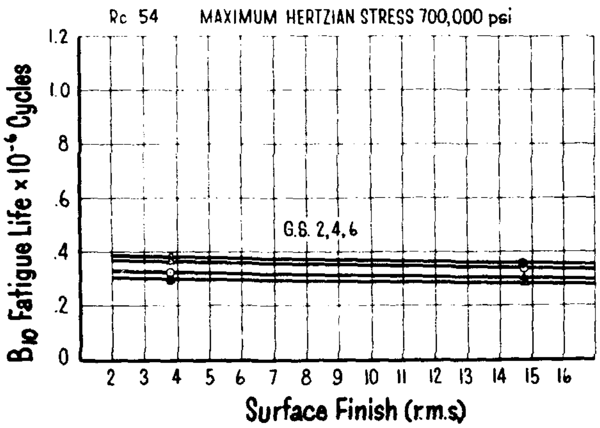


Fig. 15 B_{10} fatigue life versus surface finish

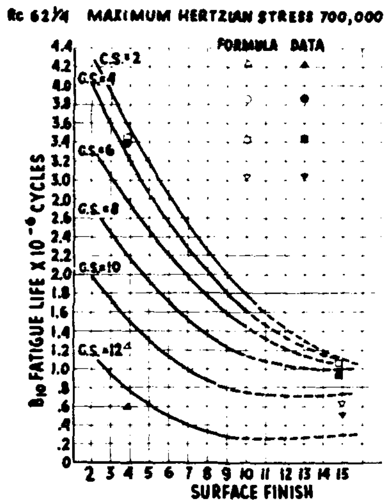


Fig. 17 B_{10} fatigue life versus surface finish

$$
\begin{aligned}
\text{Life} = \beta_0 &+ X_1\left[\beta_1+\beta_{11}X_1+\beta_{12}X_2+\beta_{13}X_3\right] \cdots \\
&+ X_2\left[\beta_2+\beta_{22}X_2+\beta_{23}X_3\right] + X_3\left[\beta_3+\beta_{33}X_3\right] \cdots \\
&+ X_4\left[\beta_4+\beta_{44}X_4+\beta_{24}X_2+\beta_{34}X_3\right]
\end{aligned}
$$

At a maximum Hertz stress of 696,440 psi (assumed to be 700,000), $X_4 = 0$, (Table 4). If we, therefore, evaluate our B_{10} lives at a stress of 700,000 psi, the modified equation reduces to:

$$
\begin{aligned}
B_{10} \text{ Life } (700{,}000 \text{ psi}) = \\
\beta_0 &+ X_1\left[\beta_1+\beta_{11}X_1+\beta_{12}X_2+\beta_{13}X_3\right] \cdots \\
&+ X_2\left[\beta_2+\beta_{22}X_2+\beta_{23}X_3\right] \cdots \\
&+ X_3\left[\beta_3+\beta_{33}X_3\right]
\end{aligned}
$$

which is limited to:

1 Maximum Hertz stress of 700,000 psi.
2 Hardnesses greater than 54 RC.
3 Grain size larger than ASTM 10.
4 Surface finishes better than 10 rms

because of the statistical data used in obtaining the equation.

Values of X_1, X_2, and X_3 are tabulated in Table 6.

QUANTITATIVE RESULTS OF MODIFIED B_{10} FATIGUE LIFE EQUATION

The graphical representation of the effects and interactions of hardness, grain size, and surface finish upon the B_{10} fatigue life on M-50 bearing material are shown in Figs. 5 to 17. Figs. 5 to 9 represent the interaction effects of grain size and surface finish upon fatigue life at different levels of surface finish. Figs.10 to 14 represent the interaction effects of surface finish and

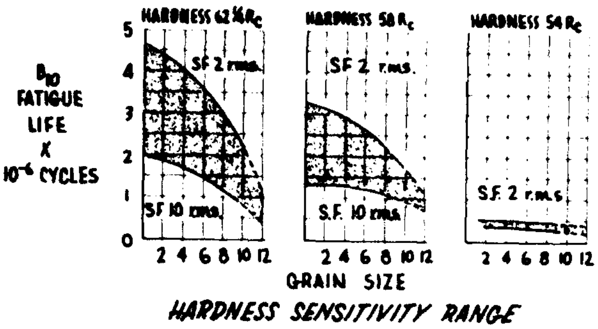


Fig. 18 B_{10} fatigue life versus grain size for various hardness and surface finishes

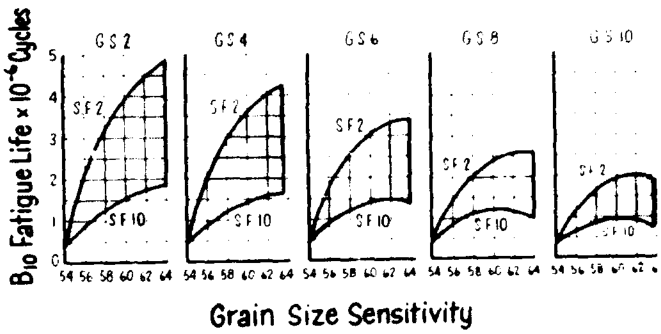


Fig. 20 B_{10} versus hardness for various grain sizes and surface finish

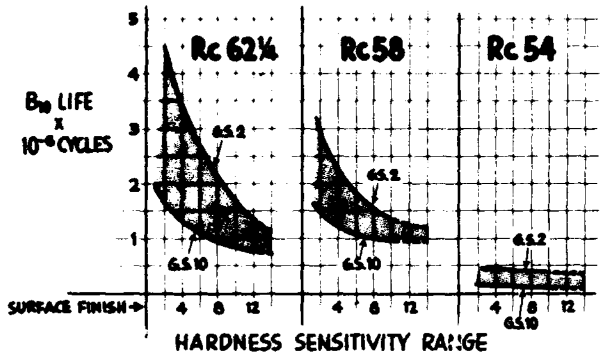


Fig. 19 B_{10} life versus finish for various hardnesses and grain sizes

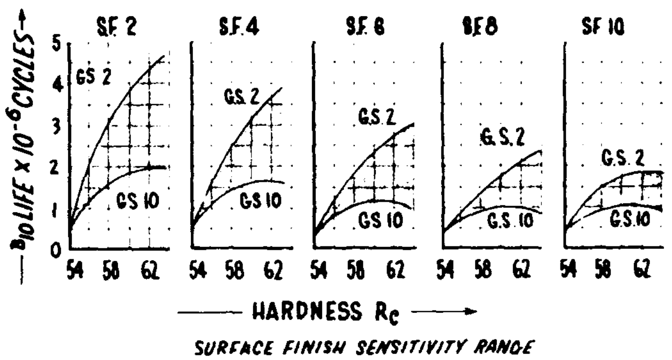


Fig. 21 B_{10} life versus hardness for various grain sizes and surface finish

hardness upon life at different grain size levels. Figs.15 to 17 represent the interaction effects of surface finish and grain size upon fatigue life at different levels of hardness. These results are graphically summarized in the grain size, surface finish, and hardness "sensitivity curves", Figs.18 to 21.

DISCUSSION OF QUALITATIVE RESULTS OBTAINED FROM MODIFIED B_{10} FATIGUE LIFE EQUATION

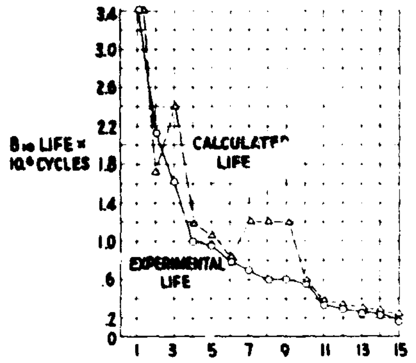
Although the quantitative results obtained from the formula are based upon a maximum Hertz stress of 700,000 psi, the qualitative results indicate the following effects of hardness, grain size, and surface finish upon the B_{10} life of M-50.

a) Effect of Hardness Upon the B_{10} Fatigue Life of M-50 (For Hardnesses Greater than 54 RC). For hardnesses greater than 54 RC, the B_{10} fatigue life of M-50 increases with increasing hardness, reaches a maximum life at an optimum hardness, and then decreases. This effect is shown in Figs.5 to 14. This optimum hardness is not a constant but varies with surface finish and grain size. This effect is shown in Fig.22.

b) Effect of Grain Size Upon the B_{10} Fatigue Life of M-50 (For Grain Sizes Larger than ASTM 10). For grain size larger than ASTM 10, the B_{10} fatigue life increases as the grain size increases. The B_{10} life approaches a constant maximum value at the large grain sizes and decreases rapidly as the grains become smaller. This effect is shown in Fig.20.

c) Effect of Surface Finish Upon the B_{10} Fatigue Life of M-50 (For Surface Finishes Better than 10 rms). For surface finishes better than 10 rms, the fatigue life increases as the surface finish improves. This life increases steadily with improving surface finish and approaches a minimum at a surface finish of 10 rms. This effect is shown in Fig.21.

d) Interaction Effects of Grain Size, Surface Finish, and Hardness Upon the B_{10} Fatigue Life of M-50 (For Hardness $>$ 54, Surface Finish $<$ 10 rms, Grain Size $>$ ASTM 10). Within the limiting regions of each variable mentioned above, the interaction effects between the variables may be best explained in terms of the "sensitivity" curves. These curves represent a measure of the sensitivity of fatigue life upon two of the variables at different levels of the third variable. The most significant



NO.	RC	G.S.	S.F.
1	62¼	3.4	3.75
2	58	7	17
3	58	7	1.5
4	58	7	9.75
5	62¼	3.4	14.75
6	58	12	9.75
7	64	7	9.75
8	62¼	10.4	3.75
9	68	2	9.75
10	62¼	10.4	14.75
11	54	3.4	3.75
12	54	10.75	3.75
13	54	3.4	14.75
14	54	10.4	14.75
15	2	7	9.75

B_{10} TEST NUMBER (FROM TABLE 2)

Fig. 23 Comparison of computed B_{10} lives and experimental results (maximum Hertzian stress - 700,000 psi

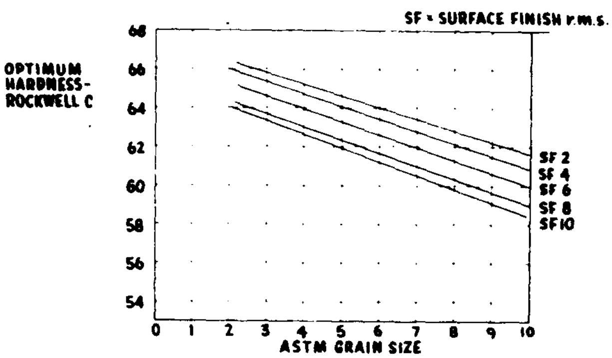


Fig. 22 Effect of grain size and surface finish upon optimum bearing hardness

results can be seen from the "hardness sensitivity" curves in Figs. 20 and 21. These curves show that at the high hardness level of $62^1/_4$ RC, the B_{10} life is extremely sensitive to grain size and surface finish. The area under this curve is a measure of this sensitivity. This sensitivity decreases at the intermediate hardness level of 58 Rc, and the B_{10} life becomes insensitive to variation in grain size and surface finish at the low hardness level of 54 RC. Results obtained from the grain size and surface sensitivity curves do not exhibit this same drastic interaction effect, although decreased ranges in predicted life occur as the grain sizes decrease and the surface finish becomes poor. This effect is shown in Figs. 18 and 19.

SUMMARY

The effects of hardness, grain size and surface finish upon fatigue life of M-50 are evaluated within certain ranges of each variable. The experimental and computed results compare favorably at the various hardness, surface finish and grain size levels, Fig.23. It should be noted, however, that this comparison is based upon limited data, which is highly statistical. In addition, further approximations are introduced into this analysis by converting all the test data to a stress level of 700,000 psi.

Acknowledgment

The author wishes to acknowledge the contribution of S. N. Miller and E. N. Bamberger of FPL Metallurgical Laboratory and J. A. Zoellner of the General Engineering Laboratory who contributed to both the experimental work and the evaluation of results given in this paper.